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Development of a Model to Simulate the Performance of Hydronic/Radiant Cooling Ceilings

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Abstract

A significant amount of the electrical energy used to cool non-residential buildings equipped with All-Air Systems is drawn by the fans that transport the cool air through the thermal distribution system. Hydronic Systems have the potential to reduce the amount of air transported through the building by separating the tasks of ventilation and thermal conditioning. Due to the physical properties of water, Hydronic Systems can transport a given amount of thermal energy using less than 5% of the otherwise necessary fan energy. This improvement alone significantly reduces the energy consumption and peak power requirement of the air conditioning system.

Hydronic Systems are particularly suited to the dry climates that are typical of California. Radiant cooling systems have been used for more than 30 years in hospital rooms, to provide a draft-free, thermally stable environment. The energy savings and peak-load characteristics of these systems have not yet been systematically analyzed. Moreover, adequate guidelines for design and control of these systems do not exist. This has prevented their widespread application to other building types.

The evaluation of the theoretical performance of Hydronic Systems could most conveniently be made by computer models. Energy analysis programs such as DOE-2 do not have the capacity of simulating Hydronic Systems yet. In this paper the development of a model that can accurately simulate the dynamic performance of Hydronic/Radiant Cooling Systems is announced. The model is able to calculate loads, heat extraction rates, room air temperature and room surface temperature distributions, and can be used to evaluate issues such as thermal comfort, controls, system sizing, system configuration and dynamic response. The model is created with the Simulation Problem Analysis and Research Kernel (SPARK) developed at the Lawrence Berkeley Laboratory, which provides a methodology for describing and solving the dynamic, non-linear equations that correspond to complex physical systems. The potential for Hydronic/Radiant Cooling Systems can be determined by running this model for a variety of construction types in different California climates.

1. Approach and Model Evaluation

1.1 Approach

Measurements have shown that radiant cooling has the potential to be an energy efficient alternative to all-air cooling systems (see [1 - 3]). Radiant cooling systems can achieve high savings, especially if used with alternative cooling sources and elements with large thermal mass. Unfortunately there is not enough design data available for these cooling systems, and the strong influence of the transient response of this cooling system causes difficulties in defining simple design rules. A survey sent to about 300 researchers and practitioners in building science showed general interest for a design tool for radiant cooling and heating systems. A building simulation program appears to be a useful tool for the understanding and predicting the thermal behavior of buildings equipped with a radiant cooling system.

Existing building simulation programs like DOE-2[1] are often not very flexible in incorporating new technologies [4]. In handling the simulation of cooling systems in general, there is a need for highly modular programs which are easily extendable and easy to use. The program RADCOOL has been designed to accurately simulate the dynamic performance of hydronic radiant cooling systems. The ultimate goal for RADCOOL is to perform as a DOE-2 SYSTEMS module, as DOE-2 cannot model radiant cooling systems yet, but it has strong capabilities in modeling the weather and HVAC components that now constitute input to RADCOOL.

1.1.1 Target of simulations

RADCOOL is designed to calculate loads, heat extraction rates, room air temperature and room surface temperature distributions. It can already be used to evaluate issues such as dynamic response and controls, and it can be extended to evaluate thermal comfort, system sizing, system configuration, and energy use. The simulation program is created with the LBL Simulation Problem Analysis and Research Kernel (SPARK) [5], which provides a methodology for describing and solving the dynamic, non-linear equations that correspond to complex physical systems.

1.1.2 Extensibility

The design of the program allows adding new modules in a straightforward way. This quality is important for the situation when new assumptions need testing. The feature of quick implementation of new modules to an existing program is generally greatly appreciated.

1.2 Model evaluation

1.2.1 Comparison with DOE-2

To evaluate the performance of RADCOOL in describing the heat transfer mechanisms inside a building structure, a SPARK "passive" test room was created. The test room simulates the thermal transfers occurring in a one-room building. The test room

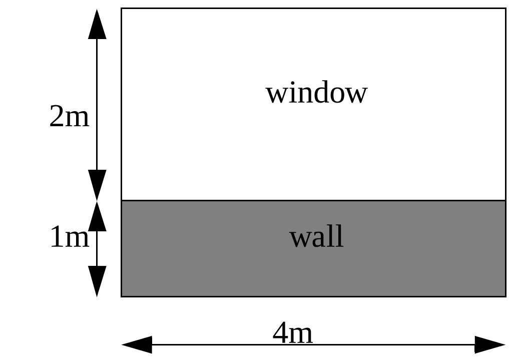
- is of rectangular shape
- may have several exterior surfaces with several windows
- can have different wall structures (wall layer sequences)
- can be ventilated
- can have several cooling systems (including non-radiant), and cooling sources.

The same test room was modeled with DOE-2, and the results of the two models were compared.

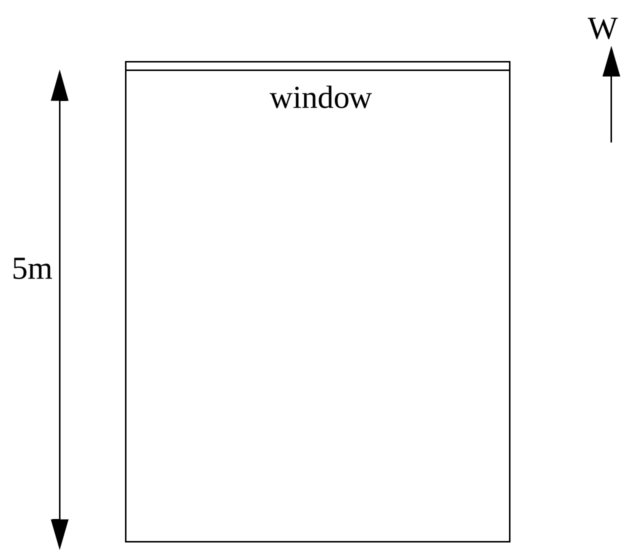
1. DOE-2 is a thermal building simulation program developed by the Simulation Research Group at LBL

1.2.1.1 The test room

For the purpose of evaluating the results from a RADCOOL calculation, the test room has the dimensions of 4m x 5m x 3 m, and all its walls are exterior. The floor is in direct contact with the ground. A window was modeled on the wall facing west. The dimensions of the test room and the geometry of the wall facing west are shown in Figure 1.



Elevation - the west-facing wall



The test room - plan

Figure 1. Test room description for performance evaluation in California

In order to compare the results of the RADCOOL simulation with the results of a DOE-2 calculation, a test room with the same dimensions was modeled in DOE-2, in the same climate, and with the same wall structure. By simulating the heat transfer in the test room using the same set of assumptions, the comparison of the two sets of results became legitimate.

The climate selected for the test room location corresponds to the Red Bluff DOE-2 weather file (a DOE-2 weather file is representative for the climate where the data acquisition system is placed). In order to match the DOE-2 model, a pre-heating period was simulated: the weather corresponding to a chosen day was repeated several times in order to provide the conditions for the building structure to adjust for the thermal storage effects. The selected test day was June 1, and the pre-heating period was set to 7 days.

No internal loads, or mechanical systems, were modeled inside the test room. The comparison of the two models is aimed at showing the similarities, or discrepancies, in their respective approaches to simulate heat transfer in a building.

1.2.1.2 The structure of the walls

In the set of tests aimed at testing the capacity of RADCOOL to simulate the room conditions in the given climate, the approach was taken to model the same structure in all 6 passive walls. In order to determine the how flexible the wall module is to changes in structure, three layer structures were modeled for the purpose of the evaluation. Figure 2 shows cross-sections of the three structures.

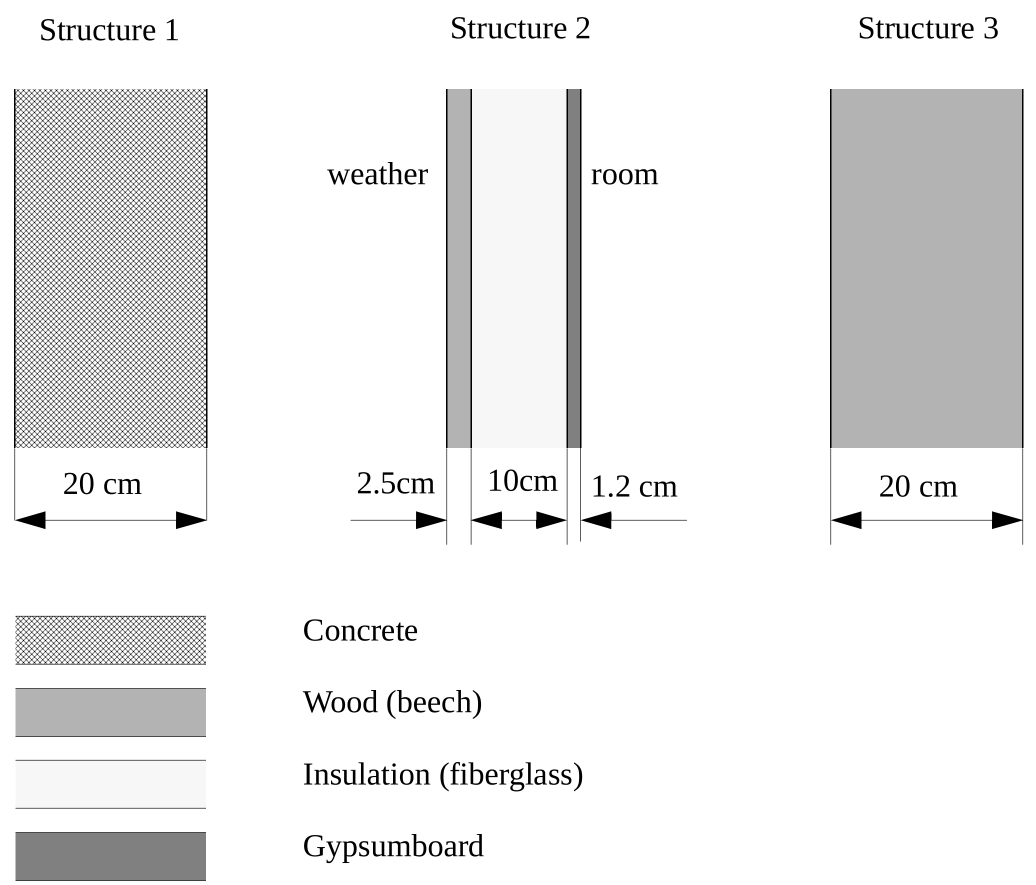


Figure 2. The material structure of the walls in the test room

The material properties of the layers and of the window glass are the following:

	Density [kg/m^3]	**Specific heat [kJ/kg K]**	**Conductivity [W/mK]**
Concrete	2400	1.04	1.80
Wood	800	2.20	0.20
Gypsumboard	1000	0.80	0.40
Fiberglass	90	0.60	0.036
Glass	2700	0.84	0.78

1.2.1.3 Results

The parameter chosen in the comparison of the two models was the indoor air temperature. Figures 3 - 5 show comparisons of the SPARK and DOE-2 models of the indoor air temperature of the test room, in the context of the outside air temperature.

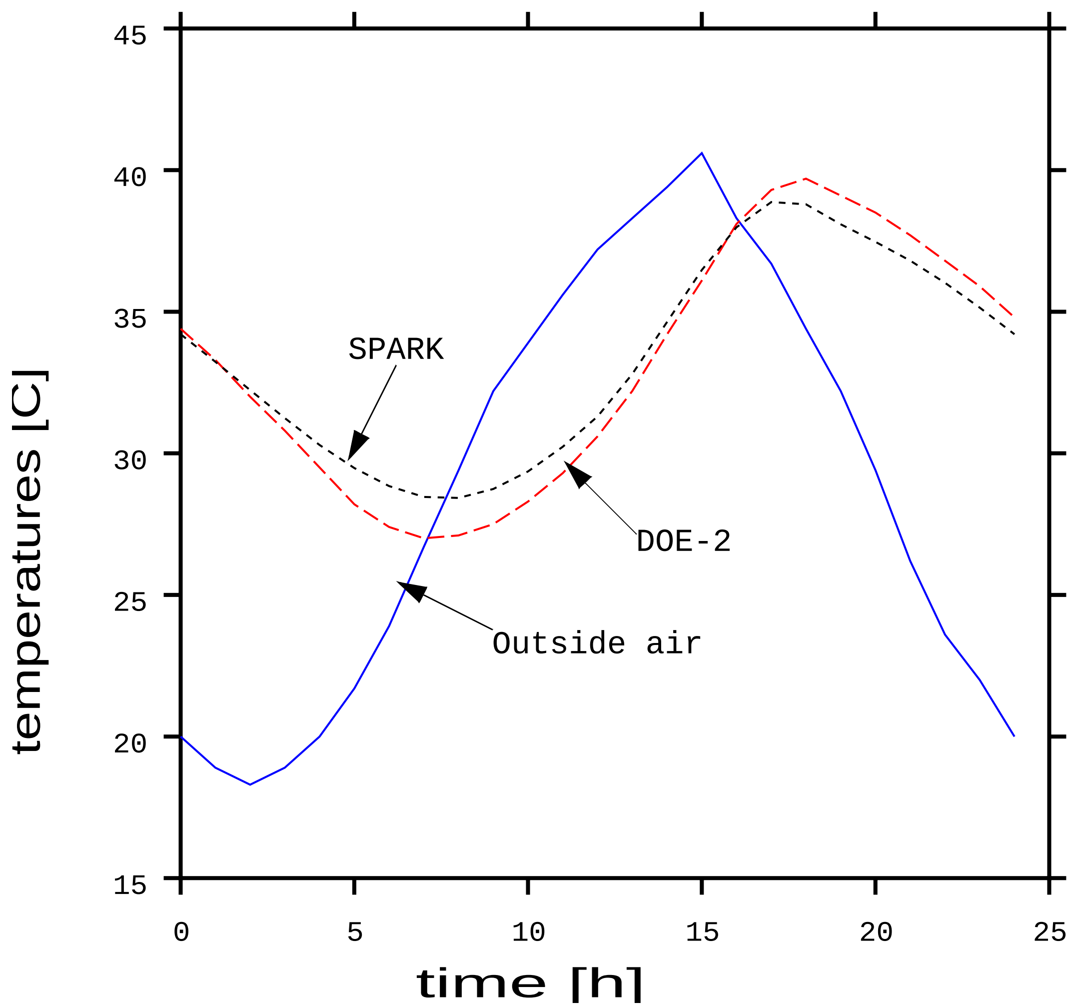


Figure 3. Indoor air temperature: structure 1 (concrete)

The first structure represents a heavy thermal mass structure. The concrete conducts to its core, and stores, the heat incident on its surface. As a result, the daily swing of the test room indoor air is dampened and delayed as compared to the outside air.

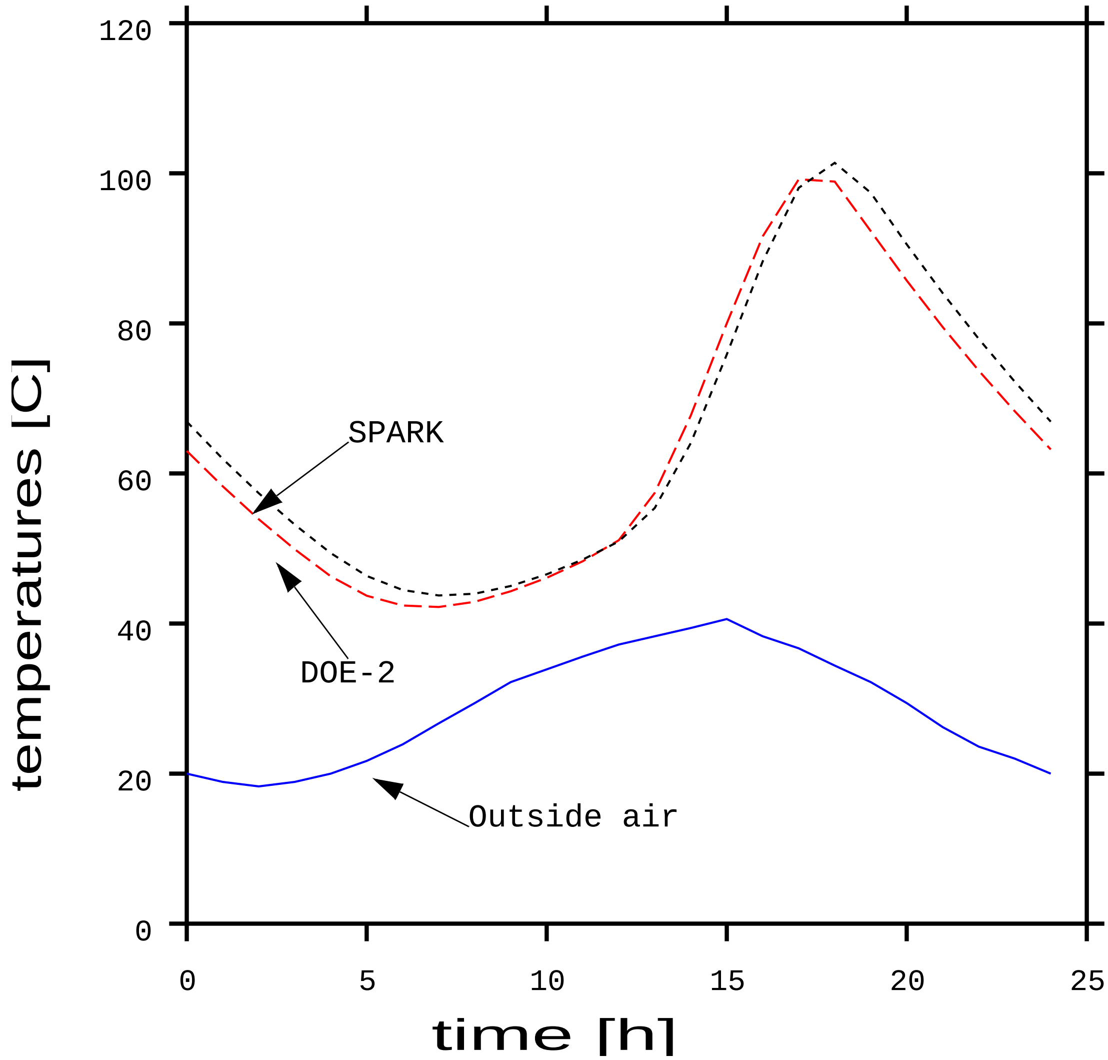


Figure 4. Indoor air temperature: structure 2 (wood - insulation - gypsumboard)

The second structure represents a custom exterior wall. An insulation layer is sandwiched between the wooden exterior and the gypsumboard interior layers. The whole structure is designed to minimize the heat conducted through the building envelope. As a result, the test room becomes very hot during the day, as the radiation entering the room through the window is not lost to the exterior by means of conduction.

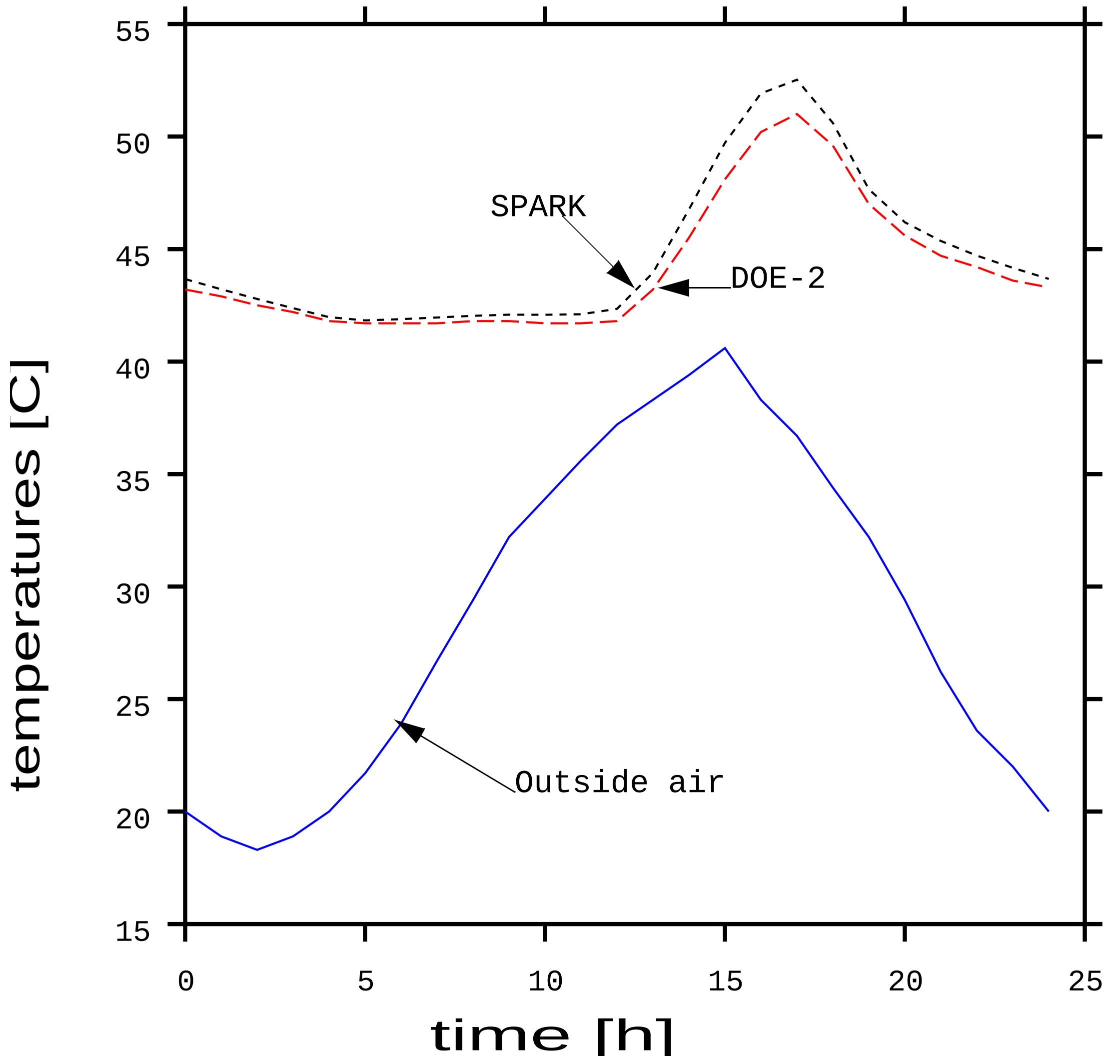


Figure 5. Indoor air temperature: structure 3 (wood)

The test room with the third structure is an “all-wood” building. Its behavior is similar to the behavior of the concrete structure, with the difference that the heat storage into the walls is not as effective as in the case of the concrete. This results from the fact that less heat is conducted towards the core of each wall, due to a much lower conductivity in the case of wood, as compared to concrete. The daily swing in the case of this third structure is dampened as compared to the outside air, but the temperatures are higher than in the case of the concrete structure.

The comparative analysis was found satisfactory as a result of the fact that the two models agreed for all three structures, within an air temperature interval of 2° C.

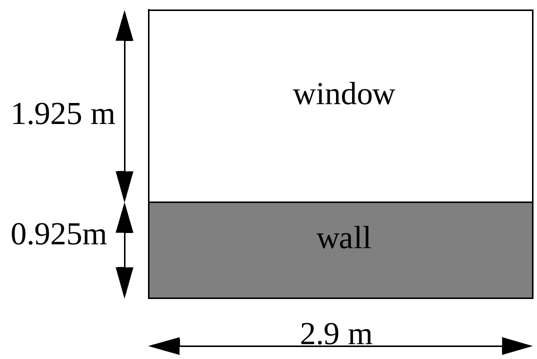
1.2.2 Comparison with measured data

The performance of RADCOOL was tested against measured data. A number of measurements were available from a building equipped with a core cooling system. The weather data at the site during the measurement period was also available for the simulation.

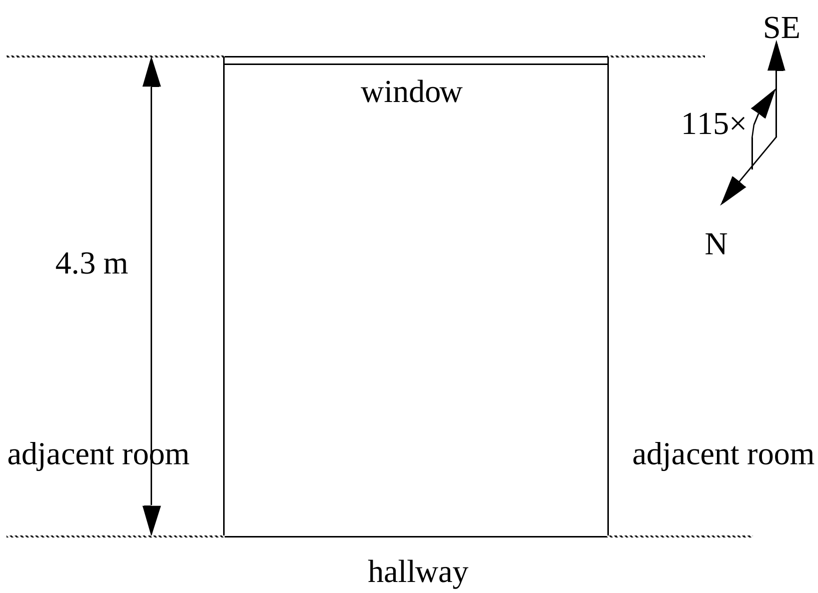
1.2.2.1 The DOW-Chemicals test room

Room: 2.9 m x 4.3 m x 2.85 m (see Figure)

- orientation: SE (65° east of south)
- position: top floor (height = 12.8 m above the ground), facade office (not a corner office)



Elevation - the SE-facing wall



The test room - plan

Figure 6. The DOW-Chemicals test room orientation and layout

1.2.2.2 Wall composition

Figures 7 and 8 show the composition of the test room walls.

The facade (exterior wall) has the dimensions of 2.9 m x 2.85 m. The lower piece is a 2.9 m x 0.925 m wall, with the following structure: 9.7 cm insulation (mineral wool) sandwiched between a 3 mm aluminum plate (outside) and a 2 mm steel plate (inside). The overall U value of the lower piece is 0.34 W/m^{2}K. The facade has a double pane window with the dimensions of 2.9 m x 1.925 m. The overall U-value of the window is 1.75 W/m^{2}K. The transmissivity of the glass is 60%, and the absorptivity for each pane is considered 5% in both direct and diffuse radiation. Automatic shades are installed over the windows; the shades are operated (closed or opened) when the overall exterior irradiance passes the threshold of 120 W/m^2. The transmissivity of the window when the shades are closed is 15%.

The interior walls consist of an 8 cm layer of sheetrock sandwiched between 2- 4 mm layers of plaster.

The ceiling (also roof for the building, as the test room is placed on the top floor) has the dimensions of 2.9 m x 4.3 m. Its structure consists of 47 cm concrete with pipes, 1 mm vapor barrier, 10 cm roofmate insulation, 1 mm tar paper, 4 cm gravel, 12 cm concrete tiles. The overall U-value of the ceiling is 0.32 W/m^{2}K.

The floor has also the dimensions of 2.9 m x 4.3 m. It represents a raised floor over the cooled concrete slab of the room below. Its structure consists of 25 cm concrete, 5.5 cm still air layer, 4 cm plywood (or chipboard) and 8 mm carpet. The overall U-value of the floor is 2.5 W/m^{2}K.

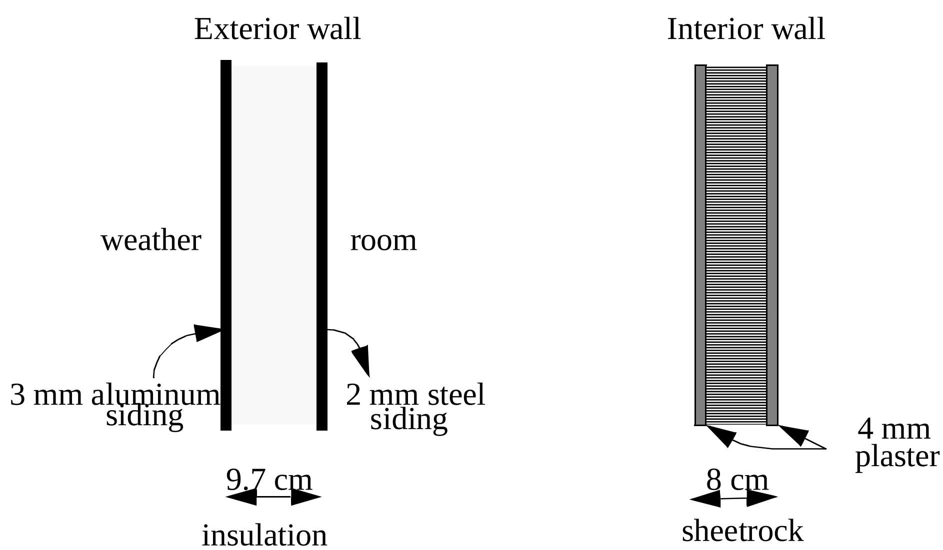


Figure 7. Vertical wall composition in the DOW-Chemical test room.

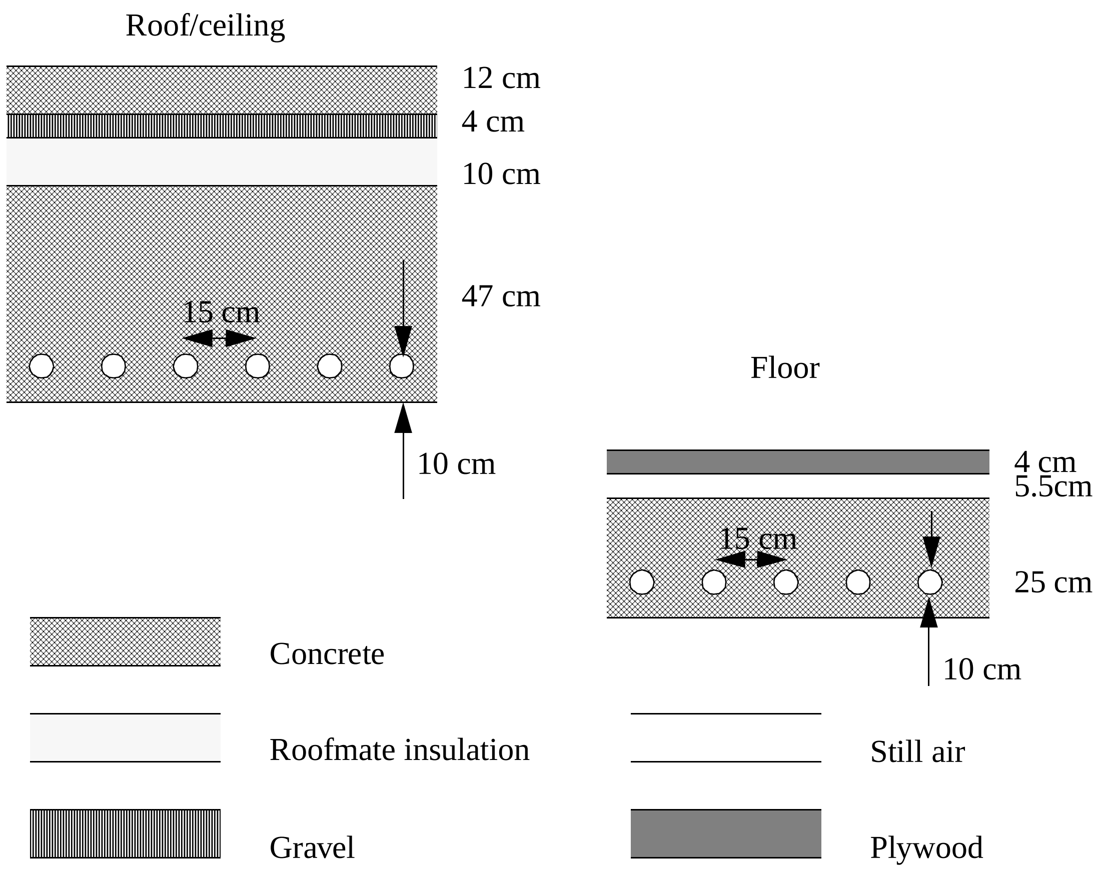


Figure 8. Roof and floor composition in the DOW-Chemicals test room.

The described materials have the following properties:

	ρ [kg/m3]	**c_t [kJ/kg-K]**	**λ [W/mK]**
Mineral wool	85	0.83	0.034
Plaster	1400	0.90	0.70
Sheetrock	1000	1.10	0.40
Concrete	2400	1.04	1.80
Roofmate insul.	33	1.40	0.032
Gravel	1650	0.90	0.70
Still air	1.2	1.00	0.59
Plywood	800	2.50	0.15
Polyethylene			0.35

1.2.2.3 Loads

1. The following **occupancy pattern** was simulated during the measurement period: 35 W/m^2 (a total of 436 W), from 8 am to 12 pm and 1 pm to 5 pm, Monday through Friday.

2. **Solar radiation**: intensities were taken from the weather recorded at a station located about 20 km away (in Waedenswil, 47.25° N and 8. 7° E). There are no tall buildings on the site, so the DOW building is not get shaded by any obstacles.

3. **Infiltration**: 0.2 ACH (7.1 m^3/h = 0.002 m^3/s)

1.2.2.4 System

1. **The cooled ceiling**: the water flow is 100 l/h per register. There are 1.5 registers on the cooled ceiling, which gives 150 l/h (0.042 kg/s) total flow. The water is supplied at a temperature that has been measured. The ceiling pipes are made out of polyethylene, have 16 mm exterior and 12 mm interior diameters, and are placed at 15 cm on center, 10 cm deep inside the concrete.

2. **Ventilation**: air at a rate of 1.1 ACH (39 m^3/h = 0.011 m^3/s) is supplied to the room over the day, when people are in. The supply rate is 0.55 ACH (19.5 m^3/h = 0.005 m^3/s) at night. The temperature of the supply air has been measured and is available for the simulation.

1.2.2.5 Boundary conditions:

1. Measurements of the air temperature in only one adjacent room are available. We used this air temperature for the other adjacent room as well. We used the measured hallway temperature as a boundary condition for the “back” wall.

2. Measurements of the air temperature inside the room are available, but not in the room below. We considered the air temperature of the room below the same as the air temperature of the test room.

3. Measurements of the air temperature 10 cm above the floor are available, and the report that came with the data states that the floor surface temperature is about equal to that air temperature. We considered that the air temperature near the floor is equal to the average room air temperature.

4. Measurements of the inlet water temperature in the ceiling of the test room are available, but not in the cooled floor (ceiling of the room below). We considered the water temperature in the cooled floor the same as the water temperature in the ceiling.

5. Measurements of the outside air temperature near the building, and at the weather station, 20 km away from the building are available. We used the temperatures measured near the building. We used the solar radiation measurements from the weather station.

6. The shade operation was “measured”, but the last two days do not agree with the inside air profile. We calculated the shade operation based on the 120 W/m^2 threshold for the first 5 days, and simulated the shades shut during the weekend.

7. In the program, 57% of the solar radiation entering the space is directed on the floor, 38% equally distributed among the vertical surfaces, and 5% is reflected back out through the window.

8. In the program, 100 W of the internal load were considered as generated by occupants (50% = 50 W convection and 50% = 50 W radiation) and 336 W by equipment and lights (30% = 101 W convection and 70% = 235 W radiation); this gives a total of 151 W (35%) convection, and 285 W (65%) radiation from internal loads.

9. In the program, the absorptivity of the window panes is considered constant, and equal to 5% for both direct and diffuse radiation.

1.2.2.6 Results

For a comparison of the simulation results with measurements, we chose the measured quantities that we had not used as input data in the program. We thus compared the following pairs of quantities:

1. The air temperature profile in the test room. The measurements provide the air temperature measured at 1.1 m above the test room floor. The simulations provide an average air temperature, representing the temperature of well-mixed air in the test room.

2. The cooled ceiling surface temperature.

3. The window surface temperature.

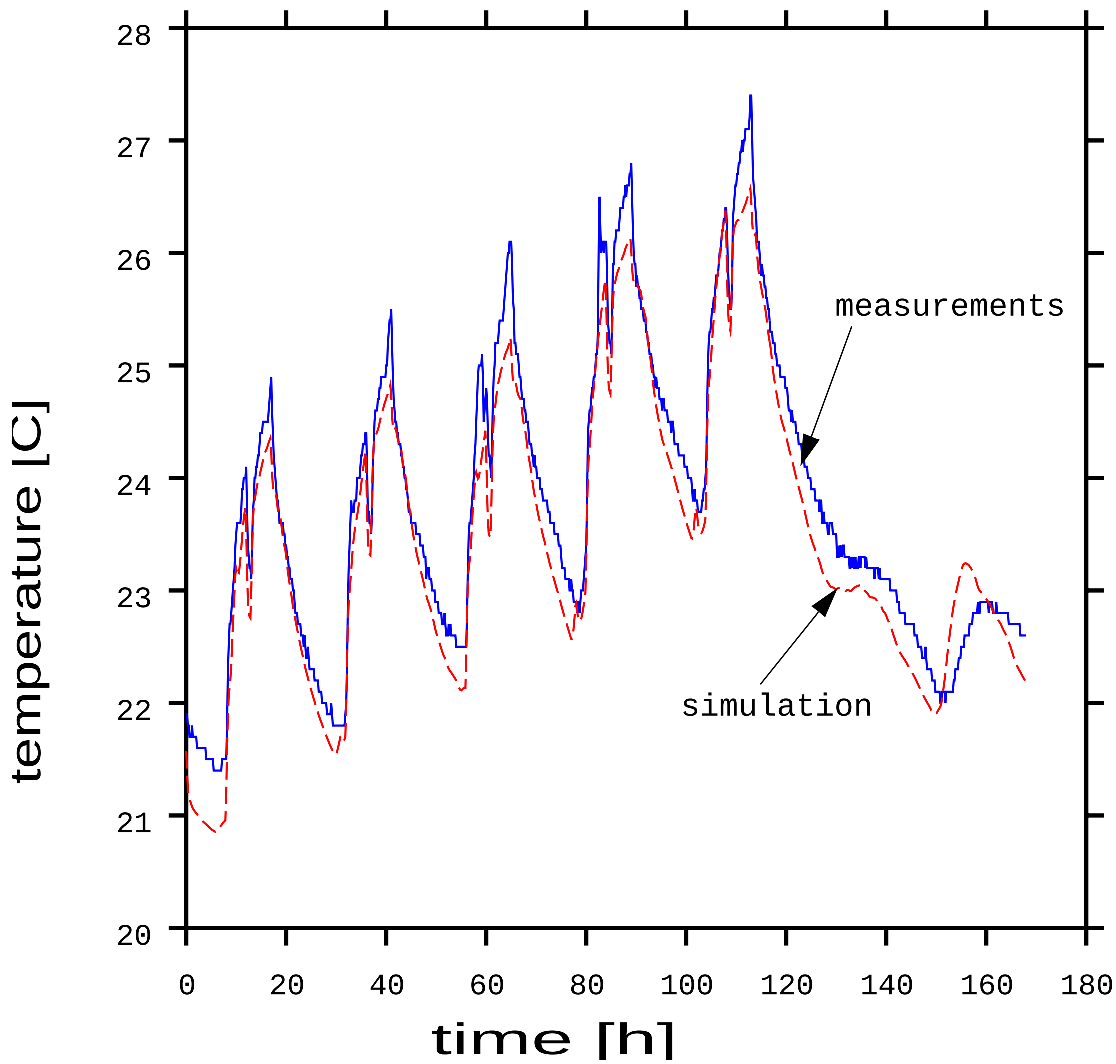


Figure 9. Average air temperature in the DOW-Chemical test room

The simulation results for the room air temperature show good agreement with the air temperature measured at 1.1 m above the floor. The last day presents the highest discrepancy, in that the simulated time of the peak temperature occurs about 4 hours earlier than the time of the measured peak. This might be due to a discrepancy between the simulated schedule of the blinds, and the real one.

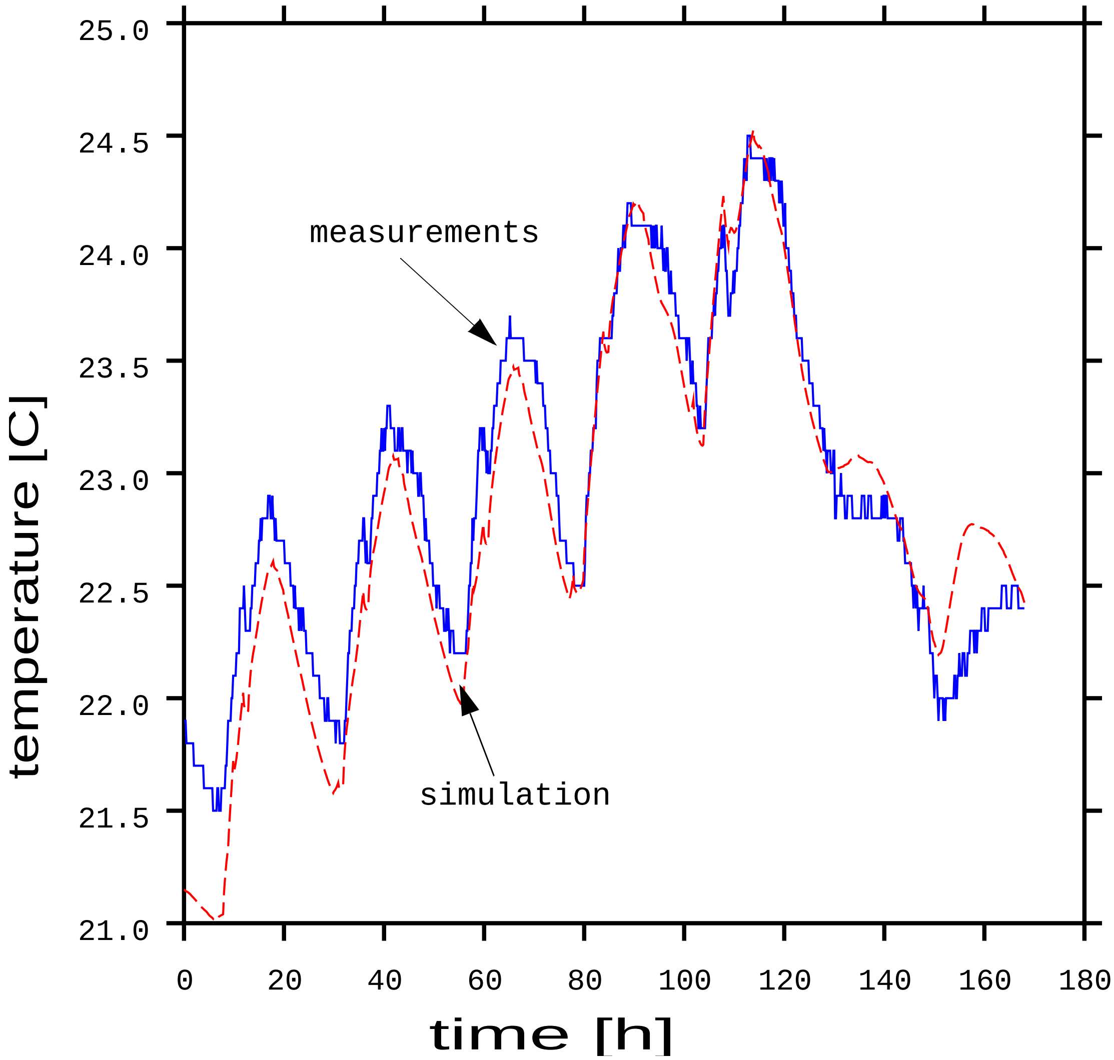


Figure 10. Cooled ceiling surface temperature in the DOW-Chemical test room

The simulation results for the cooled ceiling surface agree well with the measurements. The last 2 days present, again, the highest discrepancy, which might be due to a difference between the modeled and the real blinds operation.

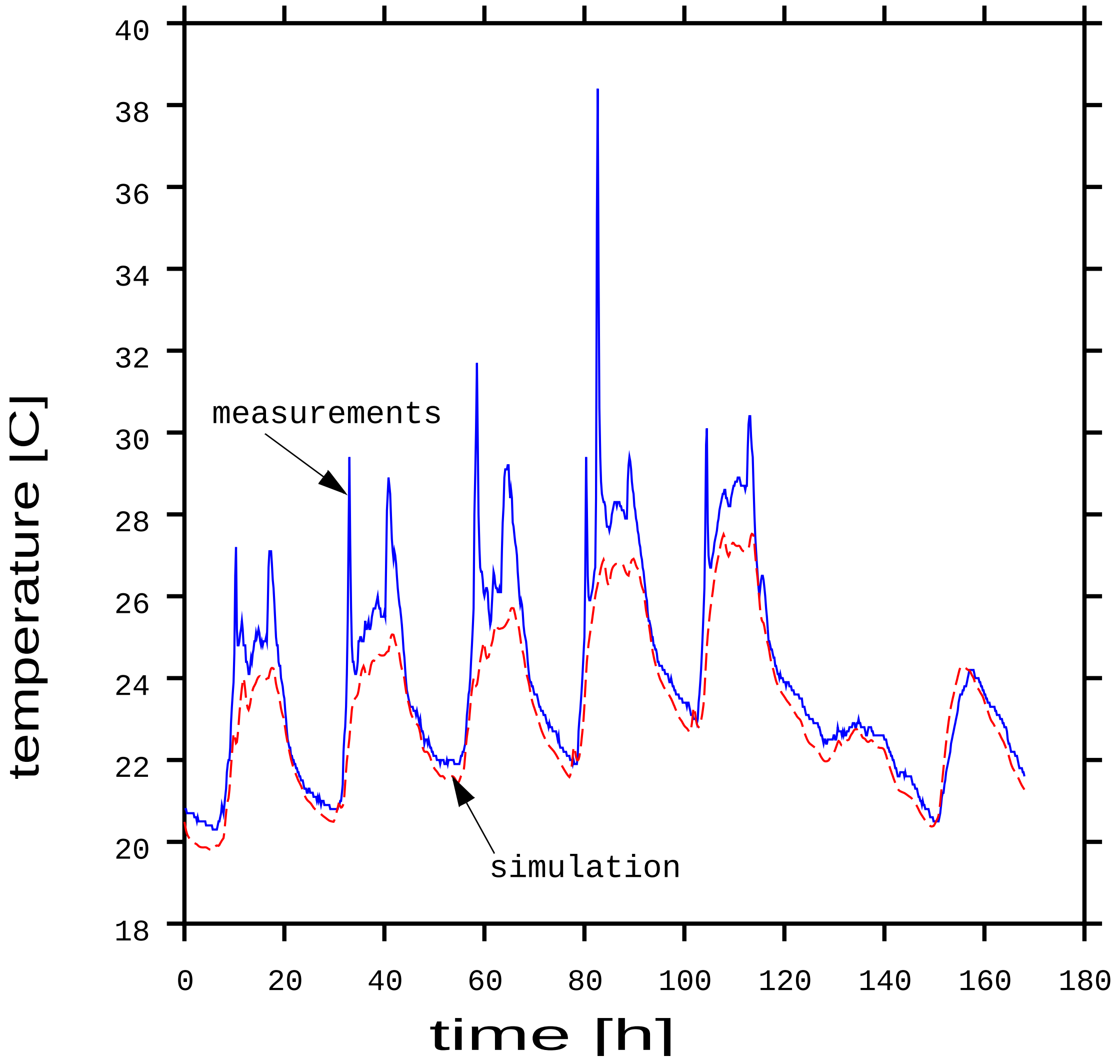


Figure 11. Window surface temperature in the DOW-Chemical test room.

The simulation results for the window surface temperature agree well with the measurements. The modeled window surface does, however, not see the morning spikes recorded in the measurements. We attribute this to the fact that in the simulation, the window surface absorptance is constant over time (5%). In reality, the glass absorptance varies with the position of the sun. This explanation is supported by the fact that there are no spikes during the last two days, when the blinds were modeled shut all the time.

2. Ceiling Performance

To evaluate the performance of radiant cooling in California climates, RADCOOL was used to model the heat transfer mechanisms in a test room. The San Jose and Red Bluff climates were selected to represent California climates, and the behavior of the same test room equipped with a radiant cooling system was studied.

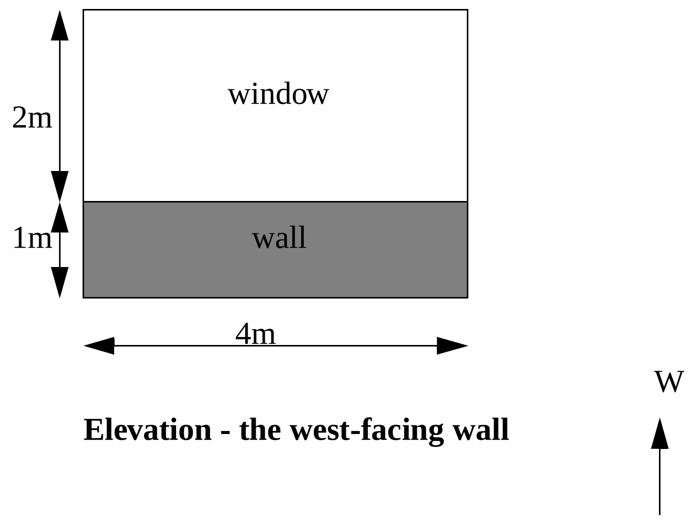
2.1 The test room geometry

The test room modeled in the study is rectangular, with the dimensions of 4m x 5m x 3 m. Only the west-facing wall is exterior. The other vertical walls, and the ceiling and floor, represent separation structures between the test room and adjacent rooms. Except for the room behind the “back” wall, all the adjacent rooms are considered to have the same interior conditions as the test room. The back wall is considered as the separation between the test room and a hallway kept at constant temperature. The dimensions of the test room and the geometry of the wall facing west are shown in Figure 1.

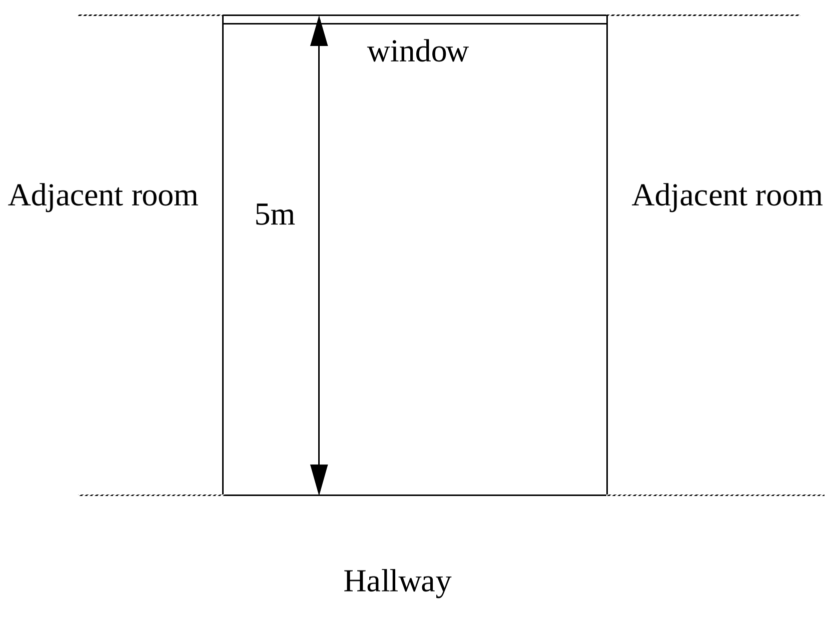
2.2 The structure of the walls

In the set of tests aimed at testing the performance of radiant cooling, the approach was to model a wall structure representative for California buildings. Figure 2 shows the cross-sections of the exterior and interior walls, of the core cooling ceiling, and of the cooling panel. The material properties of the layers, panel and of the window glass are the following:

	Density [kg/m^3]	**Specific heat [kJ/kg K]**	**Conductivity [W/mK]**
Concrete	2400	1040	0.80
Plywood	800	2.50	0.15
Fiberglass	90	0.60	0.036
Gypsumboard	1000	1.10	0.40
Stagnant air	1.3	1.00	0.57
Glass	2700	0.84	0.78



Elevation - the west-facing wall



The test room - plan

Figure 12. Test room description for performance evaluation in California

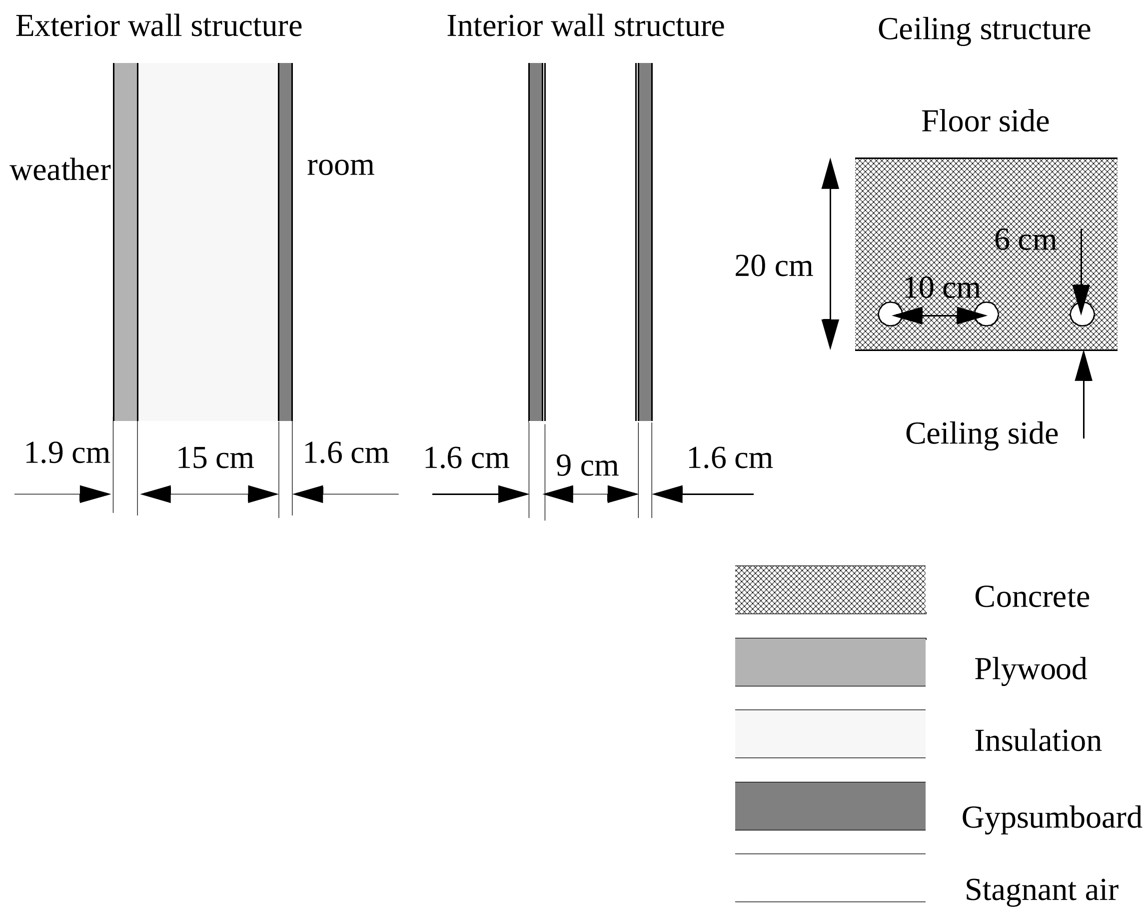


Figure 13. The material structure of the walls

2.3 Test room loads

In order to create the environment specific to an office in California, internal loads from occupants and equipment were added to the solar loads entering the test room through the window. The loads are described below.

	Load	**Schedule**
Occupants	2 people, 100W each	9 a.m. to 5 p.m.
Equipment and lights	900 W total	9 a.m. to 5 p.m.

2.4 System operation

The cooling in the test room is provided by circulating water through the pipes imbedded in the core cooled ceiling, or attached to the cooling panel. In both core cooling and panel cooling, the system operation has “mixing control”. This control functions as follows. The temperature of the air is compared to the pre-determined system setpoint temperature (see table for values). When the room air exceeds the system setpoint, the water starts flowing through the pipes. The system setpoint is also the lower limit of a pre-determined mixing band (see table for values), so at the moment when the water flow has just been turned on, the inlet water is all recirculated water. As the air temperature rises, cool water is mixed with the recirculated water. When the room air reaches the upper limit of the mixing band, the inlet water is all cool water. The mixing fraction (fraction of the cool water flow to the total water flow) is proportional to the air temperature “level” inside the mixing band.

The test room ventilation is provided by supplying outside air to the room.

The system characteristics were chosen as follows. The water flow was calculated so that the water only warms up 2 °C when it removes a load of 100 W/m^2. The inlet water temperature was chosen lower for the core cooling than for cooled panel strategy, because the large thermal mass of the ceiling produces a damping of the cool water flow effect.

	Flow	**Inlet temperature**	**Setpoint**	**Mixing band**
Cooling system	0.24 kg/s	15 °C	21 °C	21 to 22 °C
Ventilation	20 l/s	19 °C	-	-

2.5 Time periods for the runs

The time period for the runs was chosen so that the results represent the test room behavior in the worst possible case. The worst possible case was determined as the period over which the peak cooling load is occurring for a room with the same dimensions, but having no radiant cooling elements. DOE-2 calculations were made to determine the time of the peak cooling load in the San Jose and Red Bluff climates. The results show that in San Jose, the day with the highest cooling load is June 13. In Red Bluff, the day with the highest cooling load is July 15.

The run period was consequently set as follows: In San Jose, the programs ran with a 3-day pre-heating period, then with the weather corresponding to June 12-13-14. In Red Bluff, after the 3-day pre-heating period, the program ran with the weather data corresponding to July 13-14-15. The results are shown only for the last 3 days.

2.6 Results

The core cooling system was modeled to determine the conditions in a test room placed in the San Jose and Red Bluff climates respectively. The results of the simulations were brought to the form of graphs, and are presented in what follows.

Of the two graphs presented for each climate, the first shows the indoor air temperature of the test room, the operative temperature, and the outside air temperature. The operative temperature is an average between an "equivalent mean radiant temperature" and the room air temperature. The "equivalent mean radiant temperature" is calculated as a weighted average of the wall temperatures by their areas.

The second graph presented for each climate shows the room loads, and the heat removed by the water, over time. The room loads are obtained by adding together the solar radiation that enters the test room through the window, the heat generated by the people and the heat generated by the equipment present in the room. The loads introduced inside the test room by conduction through the exterior wall are not easily quantifiable, so they were not added to the loads presented in the figures.

The heat removed by the water is calculated as

$$Q_{into-water} = \dot{m}c_t(t_{return} - t_{inlet})$$

Figures 14 and 15 show the conditions that would be provided in a test room placed in San Jose, by a core cooling system operating according to the specifications in paragraph 2.4. Figures 16 and 17 show equivalent results for the same test placed in Red Bluff.

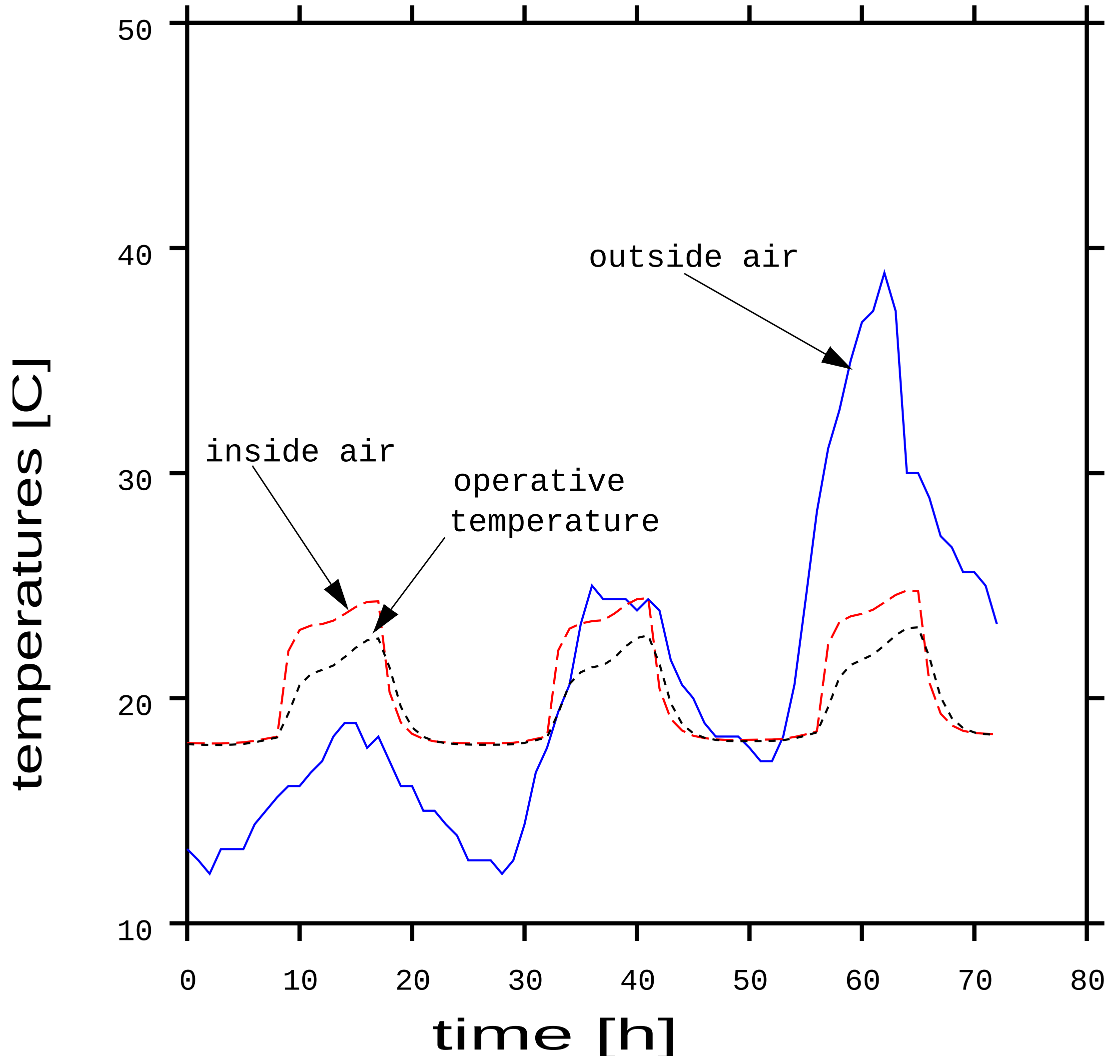


Figure 14. Core cooling in the San Jose climate. Weather for June 12 through June 14.

The test room conditioned by core (ceiling) cooling in San Jose is maintained inside a comfortable temperature range: 18 °C to 24 °C. The system allows the same temperature swing even during the last day, when the outside air temperature has a swing of 22 °C.

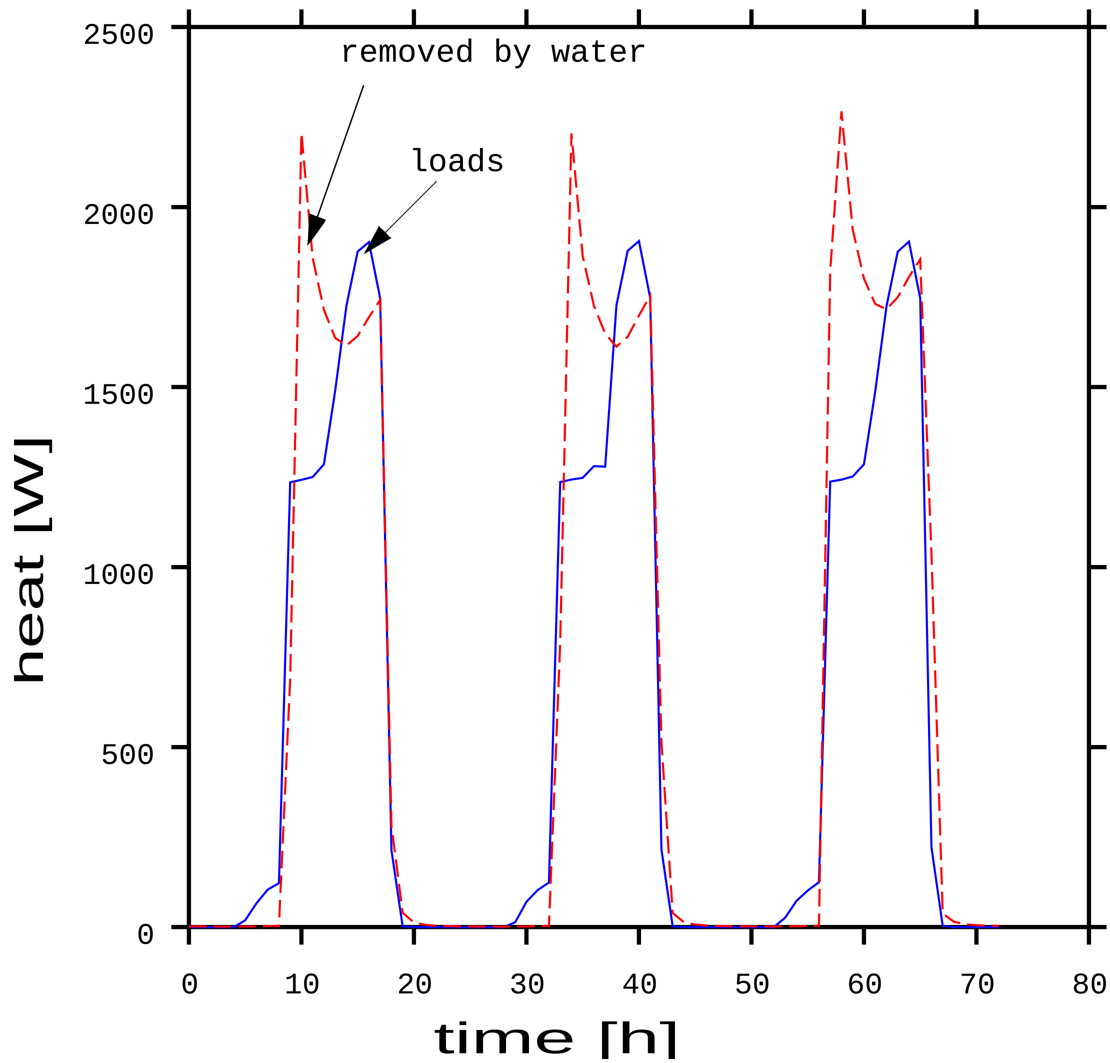


Figure 15. Comparison between loads and heat removed by the water in San Jose, for a core cooling system.

In the case of core cooling, a high initial load (due to occupant arrival and equipment start-up) results in an initial spike of the heat incident on the ceiling surface. The inside air temperature is lower than the system setpoint when this initial load appears, so the water is not flowing through the pipes at this moment. The concrete layer present between the wall surface and the water pipes stores some of this incident load. As a result, when the water starts flowing through the pipes, the heat removed by the water is higher than the initial room load. Overall, the system has the potential of removing most of the load incident on the ceiling in the San Jose climate.

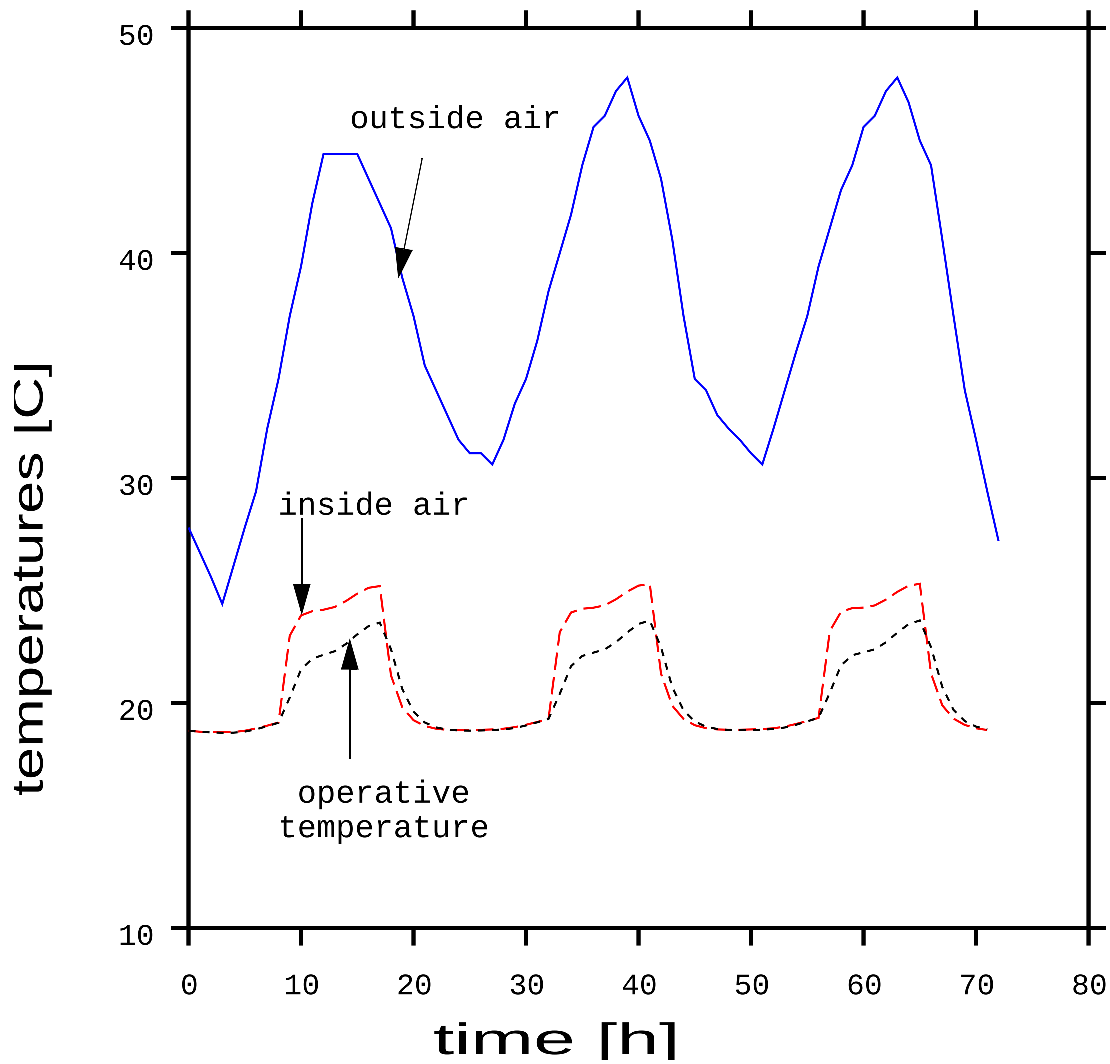


Figure 16. Core cooling in the Red Bluff climate. Weather for July 13 through July 15.

In the case of the Red Bluff climate, the outside air temperature constantly shows daily swings of 15 °C to 45°C. The cooling system can still maintain the inside air temperature within a comfortable range, 19 °C to 25 °C. The operative temperature never exceeds 24 °C.

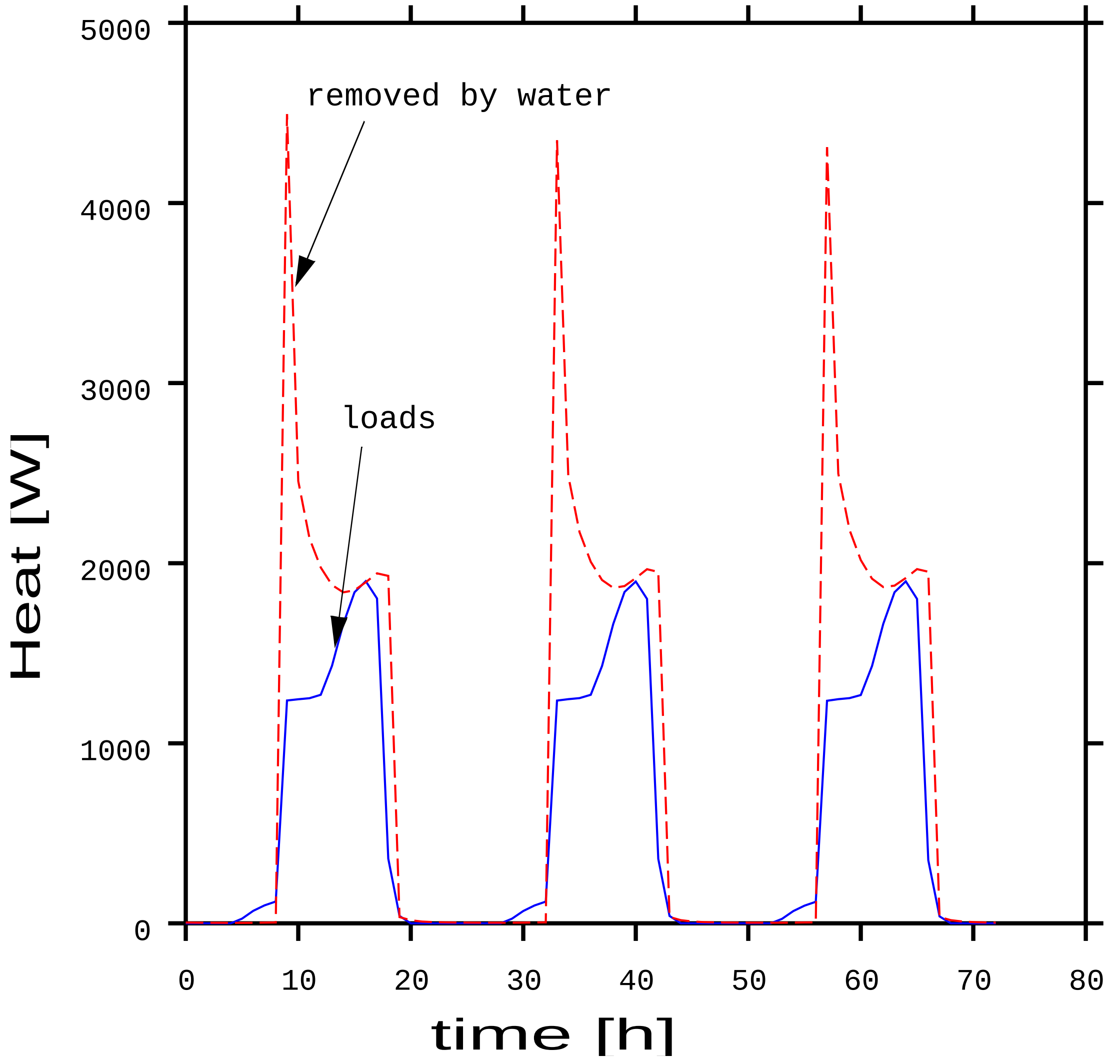


Figure 17. Comparison between the loads and the heat removed by the water in Red Bluff, for a core cooling system.

Due to the hot weather in Red Bluff, heat conduction through the exterior walls constitutes a load that significantly adds to the solar and internal test room loads. Consequently, the spike of the heat removed by the water at start-up is much higher than in the San Jose climate. Moreover, the heat removed by the water in the afternoon hours exceeds the sum of the solar and internal loads. The air temperature of the test room in Red Bluff is higher than in San Jose. Overall, the water cooling system can maintain the test room at a comfortable level.

3. Conclusions

3.1 RADCOOL provides useful results

The results in paragraph 2 show that a core cooling system is able to maintain comfortable conditions inside the test room, even in a hot climate. The fact that the cooling is performed with water at temperatures as low as 15 °C however, shows the necessity of dewpoint control in the conditioned zone. This is particularly important for a system with imbedded tubes, as condensation might form inside the slab and cause structural damage, even when the surface temperature is well above the dewpoint.

3.2 Proposed future development of RADCOOL

A few modules will have to be added to RADCOOL in order to enable it to perform better in a large variety of cases.

3.2.1 Room air stratification

The air stratification phenomenon plays an important role for radiant cooling systems. For a cooling ceiling, the more important the stratification, the more important the cooling loads that the system needs to remove. Conversely, if the air in the vicinity of the ceiling is cooled too much, it will move downwards, which will impede a displacement system from working efficiently. A secondary effect of air displacement is its bad influence on the air quality: the contaminated air that should rise and be removed through the exhaust registers. Displacement causes air to be recycled instead.

Results from research in CFD could be used to find expressions to access the air stratification, without adding too much computational cost to the program.

3.2.2 Air humidity and condensation at cool surfaces

If the surface temperatures in a room having a radiant cooling system are near the dew point temperature of the ambient air, there is a risk of condensation. Condensation is an undesired effect which may cause damage to the building materials and to the objects in the space. Furthermore, the air humidity is a comfort factor and moderate relative humidities should be maintained in spaces.

A moisture adsorbtion model for the wall surfaces can be developed [6], which would allow the examination of the relations between the thermal and the humidity behavior.

3.2.3 Thermal comfort and radiant temperature at the occupant location

A SPARK module that allows calculations of the heat exchange between the occupants of a room and the room envelope would be a useful addition to RADCOOL. Once this module is functioning, the user has a complete set of variables that indicate the level of thermal comfort.

A similar model for the that transfer between the equipment in a space and the room envelope also needs to be added to RADCOOL.

3.2.4 Heating/cooling sources

The present development of RADCOOL allows for ventilation to take place in the test room, but does not state the mechanism by which the cold (or warm) water is created, nor by which the moisture content of the air in the ventilation ducts is controlled.

There are a number of SPARK modules that model the behavior of heating/cooling sources. Ranval [7] proposed a SPARK module that describes the behavior of a cooling tower. This module can be implemented to RADCOOL. To test several cooling strategies for their performance however, it is necessary that a library of several cooling objects be created.

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5. References

1. Feustel, H.E., *Reduktion der elektrischen Spitzenlast durch Strahlungskuehlung*, Clima Commerce International, 1991.
2. Feustel, H.E., *Radiant Cooling, a Literature Survey*, LBL-33194 UC 350.
3. Feustel, H.E., De Almeida, H., Blumstein, C., *Alternatives to Compressor Cooling in California Climates - Review and Outlook*, CIEE Research Report Series, LBL 30041, UC 350, 1991.
4. Zweifel, G., *Simulation of Displacement Ventilation and Radiative Cooling with DOE-2*, Preprint to ASHRAE Transactions 1993, Vol. 99, Pt. 2, 1993.
5. Sowell, E.F., Buhl, W.F., Erdem, A.E. and Winkelmann, F.C.: *A Prototype Object-based System for HVAC Simulation*, presented at the Second International Conference on System Simulation in Buildings, Liege, Belgium, December 1986. LBL-22106.
6. El Daisty, R., Fazio, P. and Budaiwi, I., *Modelling of Indoor Air Humidity: the Dynamic Behavior Within an Enclosure*, in Energy and Buildings 19 (1992), pp.61-73.
7. Ranval, W., Rongere, F.X. and Winkelmann, F.C., *Cooling tower modeling*, Electricite de France Report No. HE-12-W3393, 1992.